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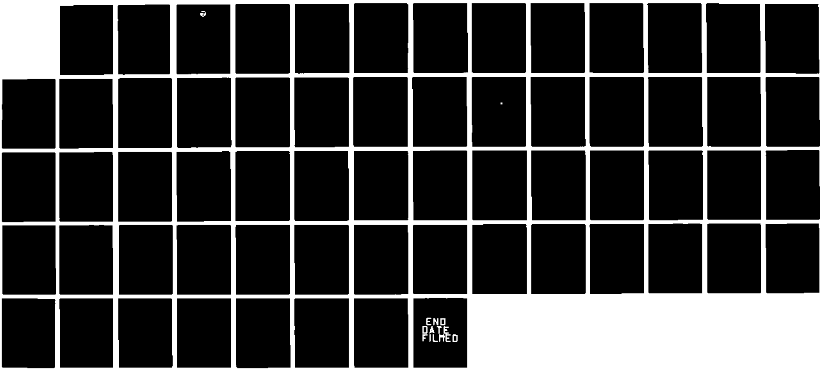

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DIGITIZER TABLETS IN COMMAND AND CONTROL APPLICATIONS: THE EFFECTS OF CONTROL-DISPLAY GAIN AND METHOD OF CURSOR CONTROL

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The purpose of this study was to assess the effects of control-display gain, target size, and method of cursor control on target selection performance with a touch tablet. The results indicated that a relatively low gain of approximately 0.875 to 1.0 resulted in faster rates of target selection and fewer entries into the target prior to confirmation than did higher gains. In addition, an absolute mode of cursor movement in which the cursor appears on the display in a position which corresponds to the placement of the finger on the touch tablet resulted in faster selection rates and fewer target entries prior to confirmation than did a relative mode of cursor movement. Finally, selection of low resolution targets was faster and more accurate than selection of high resolution targets.

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INTRODUCTION

A touch tablet (also called a graphics, digitizing, or data tablet) is a device used to input data in graphic display systems. It consists of a flat tablet or panel which is typically placed in front of and below the display. The user touches the tablet with either a stylus or with his or her finger, and the coordinate values of that location on the tablet are translated into a corresponding place on the display, usually represented by a cursor (Ritchie & Turner, 1975; Warfield, 1983). Touch tablets are often classified as locator input devices, because they provide information about the user's orientation in a "conceptual drawing space" (Foley & Wallace, 1974, p. 467).

Touch tablets may be effectively used for several types of tasks. A touch tablet is virtually the only input device which may be used for drafting or hardcopy data entry (Ohlson, 1978; Rouse, 1975), freehand sketching (Ellis, 1967; Hornbuckle, 1967; Ritchie & Turner, 1975), or producing a three-dimensional picture (Sutherland, 1974). Touch tablets are also appropriate in situations in which the user is required to select or point to an item from an array or menu (Lee & Lochovsky, 1983; Ritchie & Turner, 1975; White, in Warfield, 1983). Because of their inherent graphic nature, touch sensitive devices are slow when they are used for data entry (Pfauth & Priest, 1981).

Advantages and Disadvantages of Touch Tablets

Touch tablets and touch input devices in general have many advantages. First, the movement required and the control-display relationship are natural to many users (Foley & Wallace, 1974; Shneiderman, 1983). Similarly, Swezey and Davis (1983) suggest that touch tablets may

improve productivity because the user is not required to "translate" a command or movement into a series of keypresses. A second and related advantage is that little training is required to use a touch device (Pfauth & Priest, 1981; Swezey & Davis, 1983). Consequently, touch input devices may be useful in high stress environments, or with naive users (Pfauth & Priest, 1981).

In comparison to touch screen devices, in which the user points directly at the screen to input data, Whitfield, Ball, and Bird (1983) and Ball, Newton, and Whitfield (1980) suggest that the touch tablet provides four distinct advantages. First, both the display and the tablet may be positioned separately according to user preference. Second, the user's hand does not cover any parts of the display. Third, there are no problems with parallax due to the viewing angle of the user. Fourth, drift in the display will not affect the input. In addition, the user of a touch tablet is not likely to experience fatigue associated with continually lifting his or her hand to the screen, as is typical with a lightpen or a touch screen (Ball et al., 1980; Rouse, 1975, White, in Warfield, 1983).

Touch tablets have several disadvantages. As indicated previously, character-by-character data entry with touch devices is typically slower than with a keyboard (Pfauth & Priest, 1981). Foley and Wallace (1974) indicate that touch tablets may not provide high positioning accuracy. In comparison with a touch screen, touch tablets do not allow for direct eye-hand coordination, since they are somewhat removed from the display (Ritchie & Turner, 1975; Swezey & Davis, 1983; Whitfield et al., 1983). Finally, for those tablets which require a stylus, there may be a problem with users who are likely to misplace the stylus (Rouse, 1975).

Experimental Evidence

Despite the inherent advantages of touch tablets and their potential use for varied task types, few experimental studies have been conducted on the tablet. Whitfield, Ball, and Bird (1983) compared touch screens and touch tablets, or what they referred to as on-display and off-display input devices, for speed and error with three target selection tasks. The first two tasks involved selecting a target from a menu with low and medium resolution displays, respectively. The third task also involved the selection of a target from a menu, but several levels of target resolution were included in this one task. Total response times were a combination of both target selection (time between previous target confirmation and entry into new "target gate") and confirmation time (time from entry into target area to confirmation).

Across all three tasks the touch screen resulted in shorter total response times than the touch tablet. The longer response time with the touch tablet was attributed to the longer confirmation time required due to a need to reverse finger pressure to confirm an entry. The touch tablet was especially slow with the high resolution targets. The authors attribute this result to the direct eye-hand coordination present with the touch screen and not with the touch tablet. With respect to errors, the two input devices were comparable. The authors also reported subjective preferences. Subjects tended to be equally divided in their preferences between touch screen and touch tablet, but they indicated that the touch tablet required too much pressure, and that the surface was somewhat sticky. The authors suggest that touch input devices in general should not be used with high resolution targets or when the task is paced. However, they feel that the touch screen and the touch tablet provide comparable performance levels.

In what appears to be an earlier version of the same set of studies, Ball, Newton, and Whitfield (1980) report a comparison of the touch tablet with both the touchscreen and a trackball. This additional comparison (that is, with the trackball) was made in the third study only. The trackball resulted in somewhat slower response times than either the touch screen or the touch tablet. However, the trackball resulted in a lower error rate than the two touch input devices at all levels of resolution. The authors suggest that these differences are of no practical significance.

Albert (1982) compared the performance of seven input devices in a cursor positioning task. The devices were: touch screen, light pen, data tablet with puck, trackball, position joystick, force joystick, and keyboard. The subject's task involved positioning the cursor within a target and then entering or confirming that position. The touch tablet resulted in the second most accurate performance, with the trackball being superior. Positioning accuracy was measured as number of pixels from the target center. The touch tablet resulted in a medium positioning speed, measured in pixels per second, while the touch screen was fastest. Albert attributes this second result to the direct eye-hand coordination involved with the touch screen, as did Whitfield et al. (1983). The data tablet was ranked highly by subjects on comfort and ease of learning; the tablet was also found not to be highly tiring.

Gomez, Wolfe, Davenport, and Calder (1982) compared a trackball with a touch tablet in a tracking task. The subjects were required to superimpose a cursor over a target. Subjects were either untrained (i.e., no previous trackball experience) or were "CIC-trained" (i.e., they had experience with a trackball). The results indicated that response times were not significantly

different for the two devices. However, the trackball resulted in significantly less error than did the touch tablet, with errors measured as number of pixels away from the target. The authors attribute this latter result to the higher precision characteristics of the trackball, in particular to the fact that the hand was stabilized with the trackball and not with the touch tablet. The response times for the two devices did not differ as a result of prior subject training. However, both the CIC-trained and the untrained subjects had lower error rates when using the trackball than when using the touch tablet. The authors conclude that if tracking accuracy is not an important component of the task, a touch tablet may be a useful input device.

It should be noted that Gomez et al. (1982) allowed the subjects to use either their finger or a stylus, but they did not systematically control this variable. It is possible that the use of a stylus may have an effect on performance which should be investigated. For example, Ball et al. (1980) suggest that a stylus or joystick will complicate communication by necessitating the use of an "intermediate tool" in the data entry task. On the other hand, it is possible that a stylus may ameliorate resolution, mobility, application pressure, and surface friction problems that may be encountered with finger-operated tablets.

Several studies have been concerned with touch input devices in general (this category includes touch screens, touch tablets, and lightpens). Stammers and Bird (1980) report that air traffic controllers preferred a touch screen to touch wires and keyboards (touch tablets were not considered in this study). However, the authors indicated that the particular system under consideration needed improvement in order to decrease the current error rate.

Beringer (1979) reported that the use of a touch screen on a map display led to better performance on a plotting task in terms of errors and time to task completion than did keyboard-based systems. On other tasks, including continuous flight control and navigation information updating, the touch- and keyboard-based systems provided similar results.

English, Engelbart, and Berman (1967) compared a light pen, a knee control, a Grafacon arm, a mouse, and a joystick for speed and accuracy in a target selection task (a touch tablet was not included in the comparison). Subjects were required to move a cursor and select a target. The mouse resulted in the shortest selection times. Subjects also made the fewest errors in target selection with the mouse.

Karat, McDonald, and Anderson (1984) compared an on-screen touch panel, a mouse, and a keyboard for target selection, menu selection, and selection with typing tasks. They found that the touch panel was superior in terms of selection rate and task completion time across the task types; the keyboard was second best, and the mouse was the worst in terms of selection rate and task completion times. In addition, subjects preferred the keyboard or touch panel to the mouse for all tasks.

With respect to input devices in general, Card, English, and Burr (1978) compared four input devices for a text selection task. The input devices were: a mouse, a joystick, step keys (that is, keys which move the cursor either up/down or right/left), and text keys (keys which position the cursor at the previous or next character, word, line, or paragraph). The subjects were required to position the cursor at a target in text displayed on a CRT. Total response time was divided into homing time (time in seconds from subject's initiation of the new task to cursor movement) and positioning time (time in seconds from initial cursor movement to selection).

The results were similar to those reported by English et al. (1967); the mouse was superior to the other devices in terms of total response time, positioning time, and target selection error rate. This result occurred regardless of either the distance of the target from the current cursor position, or the target size. The authors attribute the superiority of the mouse to the continuous nature of the movement allowed by the mouse, and they suggest that less "cognitive load" is needed to translate desired into actual cursor movement. If continuous movement is one key to fast and accurate response, it is possible that the same advantage exists for touch tablets.

In relation to pointing tasks, Goodwin (1975) reported that for cursor positioning, both a lightpen and a lightgun were faster than a keyboard. Response times were measured as seconds to complete the total task. Errors were not considered. Earl and Goff (1965) found that a point-in data entry method (which appears equivalent to a lightgun) was superior with respect to input time and errors to a type-in method (i.e., a keyboard) in entering alphabetic material. This surprising result is probably due to the nature of the task. It appears that the subjects did not use the point-in method to enter one character at a time, but rather to mark or point to three words. In the type-in task, subjects were required to type three words. These results would argue for the use of a menu selection method of data entry for some tasks, but not for the use of a point-in method to input individual letters.

In summary, then, it appears that point-in and touch input methods in general, and touch tablets in particular, are useful for target or menu selection tasks if high positioning accuracy is not required. We turn now to

a discussion of several of the variables which may affect the performance of a subject using a touch pad.

Control-Display Gain

One feature which is of importance in the design of any continuous control-display interface is the control-display (C-D) gain. The C-D gain is defined to be the amount of movement which occurs on the display in response to a unit amount of movement of the control (Chapanis and Kinkade, 1972). In the present case, the question becomes: how much should the displayed cursor move in response to a movement on the touch tablet?

Swezey and Davis (1983) suggest that the area of the touch tablet should be at least as large as the display area, so that there is a minimum 1:1 correspondence between the tablet and the screen. They base this recommendation on Engel and Granda's (1975) guideline for aiding accuracy. When the gain is larger than one, a small movement of the control leads to a large movement on the display. In this case, Engel and Granda suggest that the speed of initial movement will be high, but accuracy in terms of fine adjustment suffers. When the gain is less than one, a large control movement leads to a small movement on the display, and accuracy increases; however, gross movement time will also increase. Engel and Granda (1975) do not explicitly state that a gain of one is the optimum (or even maximum) gain required, nor is there any experimental evidence at present to suggest that this is the case.

Researchers have not typically reported the C-D gains used in their experiments on touch tablets. However, a rough estimate of the possible gain may be obtained by a comparison of touch tablet and display screen dimensions. Albert (1982) used a 48.26-cm monitor with an 27.94 x 27.94-cm

data tablet. The tablet's diagonal was therefore approximately 39.37 cm. Thus, the tablet was smaller than the screen, and the C-D gain *may* have been greater than one (with no specification of the active areas of the tablet and screen, however, this is by no means a certain inference).

Gomez et al. (1982) used a 43.18-cm monitor with a touch tablet measuring 29.21- x 38.10-cm. The tablet's diagonal measurement was thus approximately 48.01 cm. Because the tablet was larger than the the screen, the C-D gain may have been less than one, although again, no firm conclusions are possible.

Whitfield, Ball, and Bird (1983) and Ball, Newton, and Whitfield (1980) used a touch tablet measuring 12.5- x 12.5-cm (thus, the diagonal was 17.68 cm) with a display which was 40.0 cm. The C-D gain was of necessity greater than one, because the displayed items in the second and third experiments covered an area on the screen which was larger than the touch tablet. It is interesting to note, therefore, that their on-display touch screen covered the entire display. Thus, their input devices are confounded with C-D gain. Performance with the touch tablet, in terms of response times and errors, might have differed if its surface area had been increased to equal that of the touch screen.

An assumption which is typically made by researchers is that there is an optimum C-D gain for any continuous control-display interface. For example, Jenkins and Connor (1949) reported that in using a knob to position a pointer on a linear scale, the optimum C-D gain was 1.18. This gain was optimum in terms of total positioning time, which included gross travel time and fine adjustment time. The authors derived a U-shaped curve which indicated an increase in travel time with decreasing gain and an increase in

adjustment time with increasing gain. This relationship is similar to that suggested by Engel and Granda (1975).

Jenkins and Olson (1952) reported that when using a lever to make settings on a linear scale, the optimum ratio between movement of the lever-tip and movement of the pointer was approximately three or four in terms of total positioning time. Thus, the optimum C-D gain, which is the reciprocal of this C-D ratio, was considerably less than one. Jenkins and Karr (1954) reported that with a joystick, a lever/pointer ratio of 2.5, or a gain of 0.4 appeared optimal. Gibbs (1962) reported that low gains of approximately 0.15 were optimal for a positional servo-mechanism and a gain of 1.3 was optimal for velocity joysticks when both systems had zero lag introduced. Thus, with these controls, a small gain appears desirable.

The last three studies which have been cited reported a primarily monotonic relationship between movement time and gain, rather than the U-shaped relationship observed by Jenkins and Connor (1949). This U-shaped relationship for rotary-knob controls may be due to the fact that a knob requires a grip-rotate-release technique; the smaller gains tested by Jenkins and Connor (1949) probably required a change in grips, leading to an increase in travel time which was not observed with the lever or pointer (Buck, 1980).

These studies illustrate two points. First, the assumption that there is an optimum C-D gain may be warranted. Second, the optimum C-D gain must be determined individually for different control-display combinations.

Unlike most researchers, Buck (1980) suggests that C-D gain is *not* the relevant factor in determining movement times. Buck points out that in previous studies, when C-D gain was increased, the width of the target on

the display typically was held constant. As a result, the latitude in the required positioning of the control, or what Buck refers to as the control target width, decreased. The resulting changes in positioning times corresponding to changes in C-D gain may be caused solely by a smaller control target width.

Buck (1980) varied control target width, display target width, and C-D gain. The subject's task was to position a cursor within a target on an oscilloscope using a joystick. The results appear to indicate that both the target width of the display and the target width of the control movement affected the amount of overshoot or fine adjustment time (time from arrival at the target edge to a 200 msec uninterrupted alignment within the target), while only the target width of the control affected acquisition or gross movement time (time from the start of movement to arrival at the target edge). C-D gain was reported not to affect either of these times, although this interpretation is unclear due to the nature of the analyses.

Buck's (1980) findings can be interpreted in terms of Fitts' law, which relates movement amplitude (or distance, A) and the width of the target (W) to movement time. Fitts' law is as follows:

$$\text{Movement time} = a + b \log_2(2A/W)$$

where a and b are constants (Wickens, 1984). This relationship essentially states that as the required movement distance (A) increases or the target width (W) decreases, movement time will increase. Buck found that a narrower control target width led to increased movement time, as would be predicted by Fitts' law.

Buck's work thus indicates the importance of considering not only the C-D gain, but also the width of the target on the display, and the tolerance

of the positioning required ofthe control. Whitfield et al. (1983) varied target resolution without changing C-D gain and reported that higher resolution (i.e., smaller) targets were selected less accurately than low resolution targets with a touch tablet. Thus, both control and display target width may have an effect on target selection tasks with a touch tablet. It should be noted that no studies to date have considered C-D gain in two-dimensional tasks; thus, it is unclear how applicable the results which have been cited regarding C-D gain are to data entry with a touch tablet.

Methods of Cursor Control

Another factor which has not been investigated with respect to the touch tablet is the manner in which the cursor responds to a control movement of the finger. For example, when an individual places his or her finger on the tablet, the display cursor may move from its current position and appear at a position which corresponds to the location of the finger on the tablet. Subsequent movement of the finger on the tablet will then produce cursor movement such that the cursor location is continually referenced to the location of the the finger on the tablet. We will refer to this method as an "absolute" mode of cursor control. A second possibility is that when the finger is placed anywhere on the tablet, the display cursor remains in its current position. Movement of the finger in this case leads to a corresponding cursor movement relative to this cursor location. This method will be referred to as a "relative" mode of cursor control.

With the relative mode, the individual can place his or her finger anywhere on the tablet and produce the desired cursor movements as long as the finger remains within the tablet boundaries. In contrast, with the absolute mode, the individual must confine his or her movements to the area

of the tablet which corresponds to the coordinates of interest on the display. Because of the differences in control movements required, it is possible that each cursor control method may have a different range of optimum C-D gains. For example, Swezey and Davis's (1983) suggestion that there be a 1:1 mapping between display and tablet appears to assume an absolute method of cursor control, which is the typical method used. With a relative mode, because the user is free to use any portion of the tablet, a smaller tablet may work well, an advantage which may be of importance if space for a keyboard is also required within the workstation. It is also possible that the user will not have to look at the tablet to position the finger, thus alleviating the problem of indirect eye-hand coordination.

In summary, the purpose of this research was to investigate the effect of C-D gain and method of cursor control on performance with a touch tablet. On the basis of pretesting, five levels of C-D gain were chosen: 0.875, 1.0, 1.5, 2.0, and 2.5. Two methods of cursor control were considered, both a relative and an absolute mode. In addition, the effect of display target resolution was examined.

METHOD

Apparatus

The task was presented on an IBM 5153 Model 1 31.75-cm color display. The display was held in an adjustable metal frame, the front of which was raised 6.86 cm.

A 27.94- x 27.94-cm Elographics E-233 touch tablet was placed on the table in front of the display. The coordinates from the touch tablet were sampled an average of once every 0.055 seconds. The tablet rested within a

66.04 cm wide by 43.18 cm high plexiglass board. The back of the plexiglass was raised 6.60 cm so that the board was at a 9 degree angle. The display and the tablet housing were placed on a table which was 73.66 cm high. Subjects were seated so that their eyes were approximately 60.96 cm away from the display.

As the C-D gain increased, the active area of the tablet necessarily decreased for absolute mode. A mat board cut to indicate the current active area and the confirmation area for each gain was placed over the tablet. The same overlays were used in relative mode to equate tablet sizes across the two modes of cursor control.

Subjects

Subjects were 20 male students from Virginia Polytechnic Institute and State University. They were paid $3.50 per hour for their participation.

Task

The center of the display contained an area approximately 14.62 cm wide and 17.07 cm high, within which rectangular targets of low, medium, and high resolution were presented. The respective areas of the targets were: 4.63 cm^2, 2.04 cm^2, and 0.51 cm^2. The corresponding dimensions of the targets were: 2.44 x 1.90 cm, 1.62 x 1.26 cm, and 0.81 x 0.63 cm. The outer right and left sides of the display contained menus of function names enclosed within rectangles of the same low, medium, and high resolution. The background of the display was black and the targets and menu were white. See Figure 1 for an example of the display.

A trial consisted of one target or function selection. At the beginning of a trial, three targets (one low, one medium, and one high resolution) were

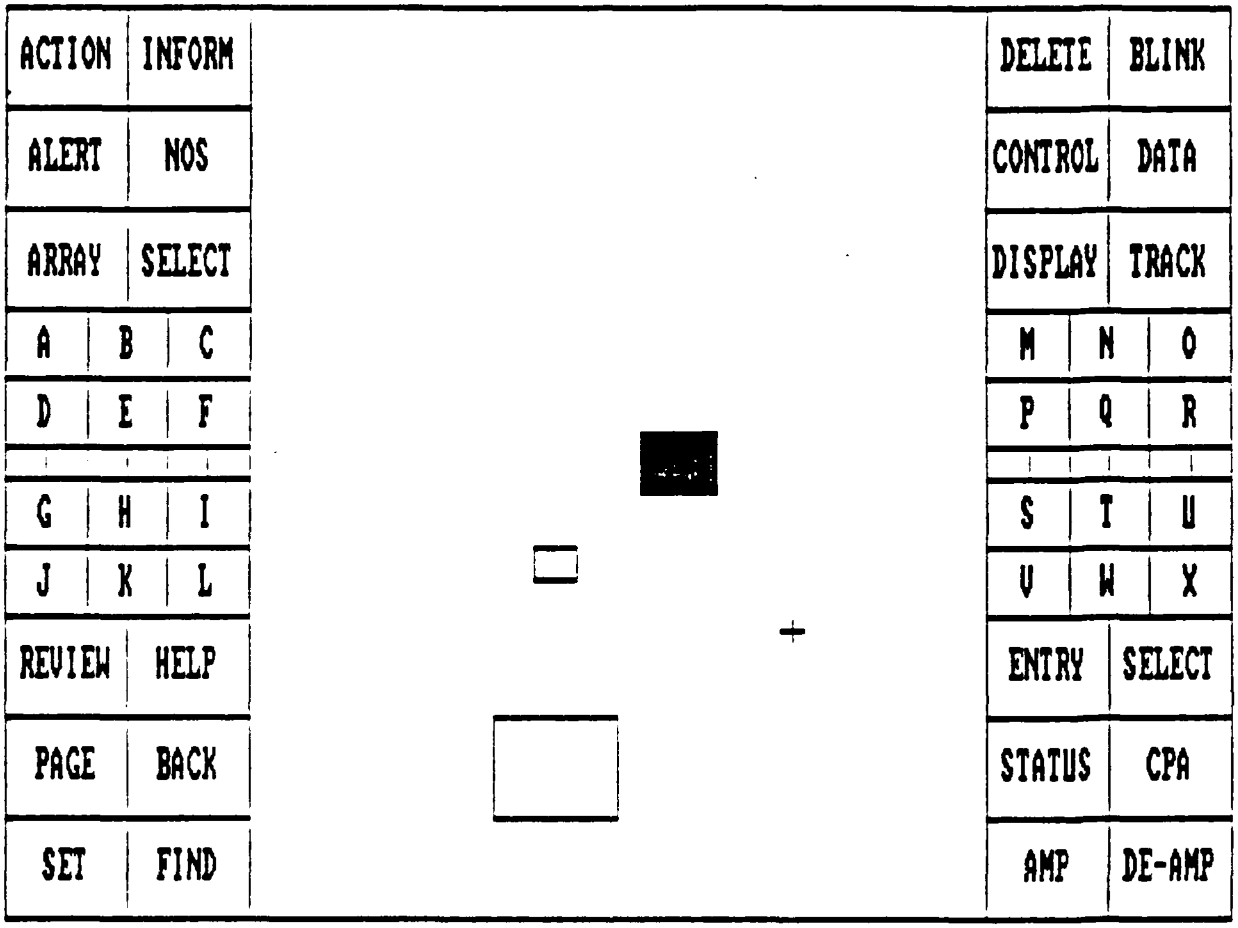

Figure 1. Example of the task display.

presented in randomly generated positions in the center of the display. One of these targets or one of the rectangles in the menu was highlighted. The subject was required to move the cursor into the highlighted area by moving his finger on the touch tablet. The subject then confirmed the selection by lifting his finger from the tablet and using the other hand to press a 27.94 cm wide by 3.81 cm deep area designated for confirmation at the bottom of the touch tablet. A high frequency tone sounded if the selection was correct, and a low frequency tone sounded if the selection was incorrect. In order for a selection to be correct, the center of the cursor had to be inside the target. Two seconds after confirmation, a new display was presented and two short tones sounded to indicate the start of a new trial.

Procedure

The three independent variables were within-subject factors. Testing for each subject took place over two days. On each day, the subject used one of the two methods of cursor control. On the basis of random assignment, half of the subjects used absolute mode on the first day and relative mode on the second day; the other half used relative mode first and absolute mode second.

On each day, the subject received one of ten counterbalanced orders of the five C-D gain values. For each of the five gains, the subject was required to select 60 targets: 20 low resolution, 20 medium resolution, and 20 high resolution. Before each set of trials, the subject was told which gain he would use for the next set and then he received a block of 15 training trials to become familiarized with the gain. Next, the subject performed the 60 target selections. At the end of the trial block, a score indicating the number of correct target selections appeared on the screen.

Subjects received a rest break between each set of trials, during which they completed a short questionnaire indicating the ease of use and the fatigue associated with the gain they had just used. After the subjects had completed the five trial blocks on each day, they were asked to rank the five gains in order of preference. At the end of the study, subjects completed a final questionnaire which asked about their preference regarding the two methods of cursor control. In addition, they were asked for their comments and suggestions about the touch tablet. The entire procedure required between two to three hours to complete over the two days. Appendix B shows the instructions which were given to the subjects, and Appendix C shows the questionnaires which were given to the subjects.

RESULTS

Three dependent measures were considered for analysis. The first was the rate of target selection, equal to the reciprocal of the total response time per target selection from target presentation to confirmation. The higher the selection rate is, the better performance is. The second measure was the number of entries into the target prior to confirmation. The larger the number of entries into the target prior to confirmation, the more difficult the fine positioning task is considered to be. The third measure was the accuracy of target selections. These measures will be considered separately.

Rate of Target Selection

An analysis of variance for rate of target selection indicated that there was a significant main effect of mode of cursor control ($F_{1,19}$=8.64, p=0.0084). The average rate of selection for absolute mode was 0.43 targets/second, while the average for relative mode was 0.40 targets/second.

Thus, absolute mode resulted in faster rates of selection averaged across all gains and target resolutions than did relative mode. Table 1 shows the average rates of target selection across conditions for absolute mode, and Table 2 shows the rates for relative mode.

There was a significant main effect of gain ($F_{4,76}$=22.52, p=0.0001). A Student Newman-Keuls test showed that while gains of 0.875 and 1.0 were not significantly different from each other, they resulted in faster selection rates than did gains of either 1.5, 2.0, or 2.5 (p<0.05). In addition, a gain of 1.5 was superior to a gain of 2.0, and a gain of 2.0 was superior to a gain of 2.5. Thus, as the gain increased, rate of target selection decreased.

There was a significant main effect of target resolution ($F_{2,38}$=1034.26, p=0.0001). A Student Newman-Keuls test showed significant differences between the three levels of resolution (p<0.05), with low resolution targets being selected at a faster rate than medium resolution targets, and medium resolution targets being selected more quickly than high resolution targets.

The mode x resolution interaction was significant ($F_{2,38}$=5.30, p=0.0093). For high resolution targets there was a smaller difference between rate of target selection for relative and absolute mode than there was for low resolution targets; however, the effect was small and was not found in the other dependent measures. The gain x resolution interaction was also significant ($F_{8,152}$=1.46, p=0.0008). The effect of gain varied depending upon target resolution -- higher resolution targets were selected at a slower rate at higher gains than at lower gains, while the selection rate of low resolution targets was not affected as much by a change in gain.

Table 1

Mean Rates of Target Selection for Absolute Mode

(targets/second)

	Gain					
	0.875	1.0	1.5	2.0	2.5	Total
Resolution						
Low	0.51	0.53	0.52	0.47	0.45	0.50
Med	0.48	0.47	0.47	0.43	0.40	0.45
High	0.36	0.37	0.34	0.32	0.29	0.34
Total	0.45	0.46	0.44	0.41	0.38	0.43

Table 2

Mean Rates of Target Selection for Relative Mode

(targets/second)

	Gain					
	0.875	1.0	1.5	2.0	2.5	Total
Resolution						
Low	0.47	0.46	0.48	0.45	0.44	0.46
Med	0.44	0.43	0.43	0.41	0.38	0.42
High	0.35	0.34	0.33	0.31	0.27	0.32
Total	0.42	0.41	0.41	0.39	0.36	0.40

The coefficient of determination (R^2) for the rate of target selection was 0.4762, which indicates that 47.62% of the overall variance in this dependent measure was accounted for by the independent variables and their interactions.

Number of Target Entries

A similar pattern of results was present for the number of entries into the target prior to confirmation. There was a significant effect of mode of cursor control ($F_{1,19}$=4.45, p=0.048). The average numbers of entries for absolute mode and relative mode respectively were 1.31 and 1.38; thus, absolute mode was again superior to relative mode. Table 3 shows the average number of target entries across conditions for absolute mode, and Table 4 shows the average number of entries for relative mode.

The main effect of gain was significant ($F_{4,76}$=35.44, p=0.0001). A Student Newman-Keuls test showed that gains of 0.875 and 1.0 did not differ significantly, while they both resulted in fewer target entries than did gains of 1.5, 2.0, and 2.5 (p<0.05). As with rate of target selection, the three higher-gains all differed significantly from each other with the number of entries increasing as gain increased.

The main effect of target resolution was also significant ($F_{2,38}$=36.33, p=0.0001). A Student Newman-Keuls test indicated significant differences between all levels of target resolution, with higher resolution targets resulting in more entries into the target prior to confirmation than lower resolution targets.

Neither the mode x *gain* nor the *mode* x resolution interactions were significant. The gain x resolution interaction was significant ($F_{8,152}$=18.40, p=0.0001). As seen in the rate of target selection measure, while gain was

Table 3

Mean Number of Target Entries Prior to Confirmation

for Absolute Mode

	Gain					
	0.875	1.0	1.5	2.0	2.5	Total
Resolution						
Low	1.09	1.08	1.11	1.20	1.21	1.14
Med	1.10	1.14	1.15	1.24	1.40	1.21
High	1.26	1.29	1.52	1.75	2.19	1.60
Total	1.15	1.17	1.26	1.40	1.60	1.31

Table 4

Mean Number of Target Entries Prior to Confirmation

for Relative Mode

	Gain					
	0.875	1.0	1.5	2.0	2.5	Total
Resolution						
Low	1.12	1.14	1.19	1.27	1.30	1.20
Med	1.18	1.19	1.29	1.39	1.44	1.30
High	1.29	1.35	1.47	1.84	2.28	1.65
Total	1.19	1.23	1.32	1.50	1.67	1.38

not as important with lower resolution targets, the higher resolution targets were more difficult to select with higher gains than with lower gains.

The R^2 for the number of entries into the target prior to confirmation was 0.2500, which indicates that 25.00% of the overall variance in this dependent measure was accounted for by the independent variables and their interactions.

Response Accuracy

The main effect of mode was not significant for this measure. There was a significant main effect of gain ($F_{4,76}$=2.99, p=0.0238). A Student Newman-Keuls test showed significant differences between all five levels of gain (p<0.05). A gain of 1.0 resulted in the smallest percentage of errors, followed by 1.5, 0.875, 2.0, and 2.5 respectively. Thus, the ordering of the gains in terms of response accuracy was not the same as seen for the rate of selection and number of entries measures. Tables 5 and 6 show the percentage of trials resulting in error for each treatment condition, for absolute and relative mode, respectively. Note that there are very few errors in any of the conditions.

There was also a significant main effect of target resolution ($F_{2,38}$=10.34, p=0.0003). A Student Newman-Keuls test indicated significant differences between all target resolutions (p<0.05), with high resolution targets resulting in the most errors, and low resolution targets resulting in the fewest errors.

Finally, there was a significant gain x resolution interaction ($F_{8,152}$=3.36, p=0.0014). As seen with the other dependent measures, acquisition of smaller targets was more affected by gain than acquisition of large targets.

Table 5

Mean Percent of Trials Resulting in Errors

for Absolute Mode

	Gain					
	0.875	1.0	1.5	2.0	2.5	Total
Resolution						
Low	1.00	1.00	0.00	1.25	0.50	0.75
Med	1.50	0.00	0.00	1.00	0.75	0.65
High	2.75	0.75	1.75	2.00	4.25	2.30
Total	1.75	0.58	0.58	1.42	1.83	1.23

Table 6

Mean Percent of Trials Resulting in Errors

for Relative Mode

	Gain					
	0.875	1.0	1.5	2.0	2.5	Total
Resolution						
Low	0.75	0.50	1.00	0.25	0.00	0.50
Med	0.75	0.75	0.75	0.25	1.75	0.85
High	0.50	0.50	1.50	2.75	3.00	1.65
Total	0.67	0.58	1.08	1.08	1.58	1.00

Although all results have been reported in an analysis of variance format, it is also possible to use the data to obtain predictive equations which would aid in determining the rate of target selection and number of target entries expected for different combinations of gain and target resolution. Such equations have been developed for the present results, and they appear in Appendix D.

DISCUSSION

All targets were selected more quickly and with fewer target entries when the subjects used absolute mode. This result may be due to the fact that the subjects were able to very quickly position their finger on the tablet in a place which corresponded to the target on the display when using absolute mode. This strategy eliminates much of the gross movement time which is necessary with relative mode, in which the subjects are required to move the cursor from its old position.

The lack of an effect of mode on errors may be due to the fact that the task in general did not result in a high error rate (see Tables 5 and 6). The subjective preferences, however, supported the performance data; 19 of the 20 subjects preferred absolute mode. In addition, several subjects suggested that performance might be enhanced by the placement of an overlay on the tablet outlining the locations of the functions depicted on the display.

The results of the present study also indicate that for touch tablets, lower C-D gains of 0.875 to 1.0 resulted in better performance than higher gains. This effect was most noticeable with high resolution targets. Thus, if the targets which an individual selects are of relatively low resolution, a gain higher than 1.0 is feasible, though not optimal. However, for high resolution targets, performance is clearly maximized with a lower gain. The

subjective responses supported this finding; with respect to ease of use and fatigue, the gains were rated from best to worst in the following order: 1.0, 0.875, 1.5, 2.0, 2.5.

The results of the present study indicate a decreasing monotonic relationship between gain and rate of target selection such that as gain decreases, rate of target selection increases. This relationship is similar to those monotonic relationships reported by Jenkins and Olson (1952), Jenkins and Karr (1954), and Gibbs (1962). It is possible, however, that with additional study, a U-shaped relationship, such as that observed by Jenkins and Connor (1949), may be found. That is, with further decreases in gain, rate of target selection may start to decrease. Thus, an optimum gain has not yet been identified with certainty for the touch tablet although a range of feasible gains has been identified.

The results of the present study indicate that high gains result in decrements in performance. Therefore, absolute mode does not appear to be appropriate for a small tablet, since a small tablet in absolute mode by definition involves a high C-D gain. However, for relative mode, tablet size is independent of gain since the location of the finger on the tablet is unimportant. Thus, it would be possible to use relative mode with a low gain and a small tablet; the user would be required to lift his or her finger several times to move the cursor across the screen. Thus, if a small tablet is necessary, relative mode may be superior to absolute mode. However, further study of tablet size and gain using a relative mode of cursor control is recommended to resolve this question.

In general, subjects selected low resolution targets at a faster rate than high resolution targets. This result agrees with previous findings that touch

tablets do not result in high positioning accuracy (cf. Gomez et al., 1982; Whitfield et al., 1983). One reason for this finding may be what Whitfield et al. (1983) refer to as fall-out error. This error may occur if the subject rolls his or her fingertip in any direction when lifting the finger from the touch tablet, resulting in a shift in the centroid of pressure on the tablet and a corresponding change in the cursor position. Gomez et al. (1982) mention the same fall-out error associated with the touch pad to which Whitfield et al. refer.

It is possible to modify the software to decrease fall-out errors. No correction was included in the present study. Whitfield et al. (1983) only included the correction when the method of confirmation was lift-off from the tablet. Lift-off from the tablet did not result in confirmation of a selection in the present study. If fall-out occurred, subjects could place their fingers back on the tablet and moved the cursor back into the target. However, fall-out was more likely to occur with high resolution targets since there was a smaller area for the cursor to remain within than there was for the medium and low resolution targets. Thus, a fall-out correction algorithm incorporated in the tablet software may act to increase the rate of selection for high resolution targets regardless of the method of confirmation.

Alternative Explanations

Earlier, it was stated that there are several factors which other authors have stated are important to consider when studying C-D gain relationships. Buck (1980) suggested that display target width and control target width are actually more important than is their ratio, C-D gain. In addition, it is possible to interpret Buck's (1980) results regarding control target width in terms of Fitts' law. These possible explanations for the present results will now be considered.

The interaction found between gain and target resolution may provide some support for Buck's (1980) hypothesis that target width is an important factor in determining performance. Selection of small targets was more affected by gain than selection of large targets. This result may suggest that the width of the target on the display is important.

The present study was not designed for the purpose of separating the effects of changes in control target width, display target width, and gain; changes in gain were achieved through a change in control target width while the overall display remained the same. Thus, gain and control target width are confounded. However, it is still possible to assess the importance of control target width by looking at different combinations of gains and target resolutions. Since control target width may be defined as the ratio of display target width to gain, it is possible to calculate the control target width for each experimental combination.

Table 7 shows the control target widths which were achieved in each of the experimental conditions. Note that a gain of 1.0 used with a high resolution target (or a display target width of 1) results in the same control target width as a gain of 2.0 used with a medium resolution target (display target width of 2). Similarly, a gain of 1.0 used with a medium resolution target results in the same control target width as a gain of 1.5 used with a low resolution target (display target width of 3). By comparing conditions which result in the same control target width with each other, it is possible to assess the effect of control target width. Thus, if this factor is critical, rather than C-D gain, the conditions which have different gains but the same control target width should not differ from each other. Student Newman-Keuls tests comparing these conditions showed that for rate of target selection

Table 7

Control Target Widths

Display Target Width*	Gain 0.875	1.0	1.5	2.0	2.5
1	1.14	1.00	0.66	0.50	0.40
2	2.29	2.00	1.33	1.00	0.80
3	3.43	3.00	2.00	1.50	1.20

* one unit equals 0.81 cm, or the width of a high resolution target

both of the comparisons were significant ($p<.05$), indicating that control target width is *not* the single critical factor for this dependent measure. For the target entry measure the opposite result was obtained; that is, the conditions with the same control target widths did not differ significantly from each other ($p>.05$).

These results are suggestive of a possible contribution of control target width to the number of target entries; however, control target width does not appear to have an effect on selection rate. Selection rate is a time-dependent measure as were the measures used by Buck (1980); thus, in comparing these results with Buck's work, it may be more appropriate to focus upon selection rate than number of target entries.

The present results are also not explained by Fitts' law. Recall that Fitts' law may be stated as follows (Wickens, 1984):

$$\text{Movement time} = a + b \log_2(2A/W)$$

As the gain increased in the present experiment, both the required movement distance (A) and the target width (W) for the subject's control input decreased. Because both A and W decreased at proportionally the same rate, Fitts' law would predict that movement time should stay the same across gains. However, the present results indicated that gains did indeed have an effect, and thus Fitts' law does not explain the results adequately. Thus, it appears that neither control target width nor Fitts' law are adequate to explain the present results.

SUMMARY AND RECOMMENDATIONS

There are three important results from the present study. First, lower gains resulted in higher rates of selection and fewer target entries than did high gains. Gains of 1.0 and 0.875 were superior to higher gains. Second,

an absolute mode of cursor control was superior to a relative mode of cursor control. Third, low resolution targets were selected more quickly and with fewer target entries prior to confirmation than were high resolution targets. In addition, high resolution targets were more affected by an increase in gain than were medium or low resolution targets. Based on these results, it appears that the optimum combination of gain, mode of cursor movement, and target resolution in the present experiment was absolute mode with a low gain (approximately 1.0) and a low resolution target.

There are several questions raised by the present research which should be pursued in future studies. First, it is possible that there are levels of gain other than those tested which would result in improved performance. The lowest gains tested (0.875 and 1.0) achieved the highest levels of performance of the five gains considered. Gains below 0.875 should be tested in future studies to determine a lower bound to the optimum range of C-D gain. In addition, it would be useful to determine whether other variables allow higher gains to be used effectively. For example, as suggested earlier, the effects of tablet size and gain with relative mode should be studied to determine whether a low gain with a small tablet would be effective. Another problem encountered when increasing gain through a change in control target width is that as gain increases, the movement of the cursor on the screen becomes less smooth due to the multiplication of the coordinates on the touch tablet by the gain factor. It is possible that higher gains may be used more effectively if the resolution of the touch tablet is increased so that movement of the cursor on the screen remains smooth as gain increases. Finally, the use of a stylus instead of a finger should be investigated because it is possible that a small point of pressure would enhance the usefulness of high gains.

There are several additional properties of the tablet which should be investigated. The use of overlays and the placement of the confirmation area may be factors which affect performance. It would also be possible to incorporate a factor in the tablet-display transfer function which would make cursor movement dependent upon finger or stylus velocity as well as displacement. That is, the effective C-D gain would increase with increasing velocity of the control input. Because the human's control input tends to be rapid during gross movement and more gradual during fine positioning, both gross movement time and fine positioning time might be minimized by such an approach.

The present results may be limited in their applicability to other tasks. It would be advantageous to study the effects of gain and mode on tasks other than those involving only target selection. Finally, the present results may be limited to small displays; before these results are applied to larger displays it may be desirable to derive a more generalized measure of gain which is based upon units of visual angle subtended by the displayed response rather than inches of movement on the display.

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APPENDIX A

INFORMED CONSENT FORM

PARTICIPANT'S INFORMED CONSENT

The purpose of this document is to obtain your consent to participate in this experiment and to inform you of your rights as a participant.

This study investigates the use of a relatively new computer input device, the digitizer or touch tablet, to perform various tasks on a graphics monitor. There are currently no specifications available to guide system designers in the use of these computer input devices. This information is needed if these devices are to be employed effectively. This research is being conducted in the Human Factors Laboratory of the Department of Industrial Engineering and Operations Research. Dr. Joel S. Greenstein and Ms. Lynn Y. Arnaut are administering this study under a contract with WESTEC Services, Inc.

Your task as a participant in this study is to use the digitizer tablet to acquire designated targets on the graphics monitor. Participation in the study is entirely voluntary. If you choose to participate you will receive instruction in the use of the digitizer tablet, you will participate in two experimental sessions, and you will be asked to complete a questionnaire regarding your use of the digitizer tablet. Each experimental session will consist of five blocks of trials with brief rest breaks between blocks. The entire experiment will require about four hours to complete. You will receive $3.50 per hour for the time that you are present, including training, rest breaks, and questionnaire administration.

We hope that this experiment will be an interesting experience for you. It is possible that at times you may feel frustrated or stressed. Your performance on the task reflects the difficulty of the task, not your personal abilities or talents.

We may videotape your activities during the experiment. These tapes would be used to verify that the experiment is running smoothly. Please note:

1. You have the right to stop participating in the experiment at any time. If you choose to terminate the experiment, you will receive pay only for the proportion of time you participated.

2. You have the right to see your data and to withdraw them from the experiment. If you decide to withdraw your data, please notify the experimenter immediately. Otherwise, identification of your particular data will not be possible, because the data will be separated from your name.

3. You have the right to be informed of the overall results of the experiment. If, after participation, you wish to receive information regarding this study, please include your address (three months hence) with your signature below. If more detailed information is desired after receiving the results summary, please contact the Human Factors Laboratory, and a full report will be made available to you.

Your participation is greatly appreciated. If you have any questions about the experiment or your rights as a participant, please do not hesitate to ask. Should you have any additional questions or problems, contact Dr. Joel S. Greenstein, Assistant Professor, at 961-6339, or Mr. Charles D. Waring, Chairman of the Institutional Review Board for Research Involving Human Subjects, at 961-5284.

Your signature below indicates you have read the above stated rights and you consent to participate. If you include your printed name and address below, a summary of the experimental results will be sent to you.

____
Signature

____
Printed Name

____
Address

____
City, State, Zip

APPENDIX B

INSTRUCTIONS

INSTRUCTIONS

In this experiment you will be required to select a target presented on the display as quickly and as accurately as possible by moving the cursor into the target and then confirming your selection.

On the table in front of you is a touch tablet. At the bottom there is a large rectangle. This area is the confirmation area, as shown in the following diagram.

CONFIRMATION

Press the confirmation area now, and an example of the display will appear. Do not press the touch tablet again until you are instructed to do so.

The cursor is the crosshair (+) which you see in the center of the display. A target can be one of the boxes in the menu that you now see on the left and right sides of the display, or it may be a box which will appear in the center area of the display.

At the beginning of each trial, a display like the one which is now on the screen will be presented. One of the targets will be highlighted (filled in with white). The highlighted target is the one you must select. To do so, you will place your finger on the touch tablet and move your finger until the cursor is inside the target.

The center of the cursor must be inside the highlighted area for your selection to be correct. During the practice sessions, it is a good idea to try putting the cursor on the sides and corners of the targets and then confirming your selection. You will then have an idea as to when a selection will be considered correct. When moving your finger on the touch tablet, be sure that your hands do not touch any other area of the tablet.

Once you are sure that the cursor is inside the target, lift your finger and *use your other hand* hand to press the confirmation area on the tablet. If your target selection was correct, a high frequency auditory tone will sound. If your selection was incorrect, a low frequency tone will be presented.

After a two-second pause, a new target will be presented and two brief tones will sound to indicate the beginning of the next trial. As soon as the two tones sound, the trial begins, and the clock will begin to time your response. Be sure to remove your finger from the confirmation area before you begin to move the cursor with your other hand.

You will complete five sets of trials today. In each set, the *control-display gain* will be changed. Control-display gain refers to the amount of cursor movement produced on the screen in response to movements of your

finger on the touch tablet. In some sets, when you move your finger on the tablet, the cursor will move farther on the screen. In other sets, the cursor will move a shorter distance than your finger has moved. In one set, the cursor will move the same distance as your finger moves on the tablet.

Before you start each set of trials, the experimenter will tell you the control-display gain that will be used. You will be given a chance to practice with that gain value before the actual timed set of trials begins.

You will be required to select 60 targets in each of the five sets of trials. Try to select the targets as quickly as possible while minimizing errors. At the end of each set, a message will be displayed informing you that the trial block is finished. In addition, the number of correct target selections for that set of trials will be presented. At that point, inform the experimenter that the trial block is completed. You will then receive a rest break before the next set begins.

When you are ready to begin, the experimenter will explain how to control the cursor and you will then be trained on the first set of trials.

Do you have any questions?

INSTRUCTIONS FOR CURSOR MOVEMENT - ABSOLUTE MODE

When you place your finger on the tablet the cursor will move to the position on the display which corresponds to the position of your finger on the tablet. Movement of your finger across the tablet will move the cursor from this *new* position. Thus, note that every time you place your finger on the tablet, the cursor will change position on the display.

There are several possible strategies which you may use. At the beginning of a trial, you can attempt to place your finger in a spot on the tablet which corresponds to the highlighted target on the display and then continue to move the cursor from that position. Alternatively, you may wish to simply place your finger anywhere on the tablet and then move the cursor after seeing where it appears on the display. The choice of strategies is up to you. Use the training *sessions before each* set of trials to practice both methods. Then, choose the one with which you are most comfortable. Once you have chosen a strategy, use that method throughout that set of trials.

Do you have any questions?

INSTRUCTIONS FOR CURSOR MOVEMENT - RELATIVE MODE

When you place your finger on the tablet the cursor will stay where it is on the display. Movement of your finger across the tablet will move the cursor from this *current* position. Thus, note that every time you place your finger on the tablet, the cursor remains where it is on the display.

You may place your finger anywhere on the tablet to initiate cursor movement. If your finger touches the edge of the tablet, simply lift your finger up and place it down elsewhere on the tablet.

Do you have any questions?

APPENDIX C

QUESTIONNAIRES

Subj ________
Gain ________
Mode ________

How easy was this gain value to use?

1	2	3	4	5
very difficult		acceptable		very easy

How fatiguing did you find this gain value?

1	2	3	4	5
very fatiguing		somewhat fatiguing		not at all fatiguing

Subj ________
Mode ________

Please rank the five gains in order of preference, with 1 being the most preferred and 5 being the least preferred.

0.875	________
1.0	________
1.5	________
2.0	________
2.5	________

Subj ______

Which method of cursor control do you prefer? (Check one)

absolute ______

relative ______

no preference ______

Why? ______________________________

____

____

____

APPENDIX D

PREDICTIVE REGRESSION EQUATIONS

Both gain and target resolution are continuous variables; thus, it is possible to develop predictive regression equations in terms of these variables. These equations may be used to predict the response of an individual using a touch tablet given a new combination of gain and target resolution. Because the analysis of variance found a significant effect of mode of cursor movement on target selection rate and number of target entries prior to confirmation, a separate regression equation was derived for each mode. That is, since mode is a categorical variable it is more useful to predict responses for each mode than it is to include mode as a factor in a regression equation. No equations will be developed for the percentage of errors because there were not enough errors to adequately model their occurrence.

In the equations which are presented, the area of the target in square inches has been used as the unit for the target resolution. The symbol 'G' refers to gain and 'A' refers to target area. Four equations have been developed, one for each combination of the two modes of cursor movement and the two dependent measures. The equations and some statistics for each one are presented, and a discussion follows outlining the uses and limitations of the equations.

Absolute Mode/Rate of Target Selection (targets/second)

$$\text{Rate} = 0.3121 + 0.0235\ G + 0.683\ A - 0.0229\ G^2 - 0.563\ A^2 + 0.0118\ G{\times}A$$

$R^2 = 0.2810$

$s^2 = 0.0141$

$Cp = 6.0$

Lack of fit : $F = 2.094$, $p = 0.0267$

Absolute Mode/Number of Target Entries

$$\text{Entries} = 1.2239 + 0.1659\ G - 1.5022\ A + 0.1069\ G^2 + 2.3226\ A^2 - 0.6804\ G{\times}A$$

$R^2 = 0.1088$

$s^2 = 0.6649$

$Cp = 6.0$

Lack of fit : $F = 4.398$, $p = 0.0001$

Relative Mode/Rate of Target Selection (targets/second)

$$\text{Rate} = 0.2969 + 0.0257\ G + 0.5225\ A - 0.0223\ G^2 - 0.4724\ A^2 + 0.0482\ G{\times}A$$

$R^2 = 0.1900$

$s^2 = 0.0168$

$Cp = 6.0$

Lack of fit : $F = 0.879$, $p = 0.5442$

Relative Mode/Number of Target Entries

$$\text{Entries} = 1.1347 + 0.2870\ G - 1.1271\ A + 0.0778\ G^2 + 1.9001\ A^2 - 0.6855\ G{\times}A$$

$R^2 = 0.1056$

$s^2 = 0.6796$

$Cp = 6.0$

Lack of fit : $F = 6.503$, $p = 0.0001$

August 26, 85

END
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